Minority Ion Measurements During ICRF Experiments in Alcator C-Mod*

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Summary

ICRF is the primary auxiliary heating in C-Mod where both H or $^3$He minority and mode conversion regimes are utilized. For transport analysis, the power deposition profile is critical and measuring the resulting fast ion distribution provides a direct means to constrain and validate ICRF simulations used to calculate power deposition. In mode conversion, measurement of the minority ion density, temperature, and velocity profiles is critical for the wave physics and may provide some insight into the fundamental physics of flow drive.

Using active charge exchange, the He$^{+1}$ 4686Å or H 6563Å line is observed with a high throughput spectrometer via 30 poloidal and toroidal views which facilitate measurement from the core to the edge. The greatest progress has been made in D($^3$He) (minority in parentheses) because of better S/N than for D(H). This is due largely to the bright ambient D emission which interferes with measurement for the latter. Initial results from fast ion detection, minority ion density, temperature, and velocity profiles will be reported for D($^3$He) discharges. Diagnostic design for H minority measurements will also be presented.
Introduction

- Fast ions are energetic ions that are not in thermal equilibrium with bulk plasma ions.
  - generated during ICRF minority heating (MH)
- Diagnostic neutral beam is used for active charge exchange recombination spectroscopy (CXRS)
- The CXRS diagnostic has been adapted to measure emission at the He$^{+1}$ 4686Å line or the H$_\alpha$ 6563Å line
  - Measure H or $^3$He fast ions in MH plasmas (FICXS)
  - Measure $^3$He density, temperature, and velocity, which is used to verify ICRF power deposition simulation
- Fast ions can be detected by a departure from Gaussian line shape.
• The light is collected by two optical periscopes (red and blue) and transmitted through two fiber bundles to holographic imaging spectrograph.

• Spectrograph is set up to accept the light from up to 45 spatial channels and spectrally disperse them onto the CCD detector, while keeping them spatially separated.

Two Plasma Views

Poloidal coverage: 0.650m to 0.896m ($\rho \approx 0$ to 1)
Toroidal coverage: 0.720m to 0.839m ($\rho \approx 0.29$ to 0.79)
Physics of CXRS/FICXS 1

Position smearing effects:
(for 30 keV hydrogen)

a. neutral beam width: ~14 cm
b. halo: ~12 cm
c. gyroradius: ~0.5 cm \( \rho = \frac{mv_f}{eB} \)
d. fast neutral travel: ~5.5 cm

Interactions (partial list):

1. DNB charge exchange
   \( H_B^0 + A_f^{+Z} \rightarrow H_f^+ + (A_f^{+Z-1})^* \)
2. Halo charge exchange
   \( D_0^0 + A_f^{+Z} \rightarrow D^+ + (A_f^{+Z-1})^* \)
3. Collisional excitation/de-excitation
   \( (A_f^{+Z-1})^* + e \rightarrow (A_f^{+Z-1})^{**} + e \)
   \( (A_f^{+Z-1})^* + i \rightarrow (A_f^{+Z-1})^{**} + i \)
4. Spontaneous emission
   \( (A_f^{+Z-1})^{**} \rightarrow (A_f^{+Z-1})^* + h\nu \)
   \( \lambda = \lambda_0 \left(1 + \frac{v_f}{c} \cos(\theta)\right) \)
5. Ionization or escape (for H)
   \( H_f^0 + e^- \rightarrow H_f^+ + e^- + e^- \)
Physics of CXRS/FICXS 2

- Low Z ions are fully stripped, so do not have line emission
- The neutral beam fires into plasma and donates electrons to the recipient ions, either by direct exchange or by exchange with the halo of neutral deuterium that forms around the beam
- The initial charge exchange can sometimes leave the recipient in an excited state, or the recipient can be excited/de-excited by collisions
- The excited ion or atom emits a spectrum which contains a Doppler pattern which depends on the distribution function
- The spectrum can be analyzed for density, temperature, velocity, or presence of fast ions
- The emission spectrum is given by:

$$\varepsilon(\lambda) dV d\Omega = \frac{1}{4\pi} \sum_i n_i \int f(\vec{v}) \sigma \left( \frac{1}{2} m |\vec{v} - \vec{v}_i| \right) \delta \left[ \lambda - \lambda_0 \left( 1 + \frac{v \cos \alpha}{c} \right) \right] d^3 v$$
He II 4686Å Spectrum from one channel

- Neutral beam is modulated in synch with detector framing
- Subtract background by taking: beam on data – beam off data
  - large background from edge emission and bremsstrahlung

Spectral region near He II 4686Å line

Area of He II 4686Å line vs time

Beam enhancement

Neutral beam is modulated in synch with detector framing

Subtract background by taking: beam on data – beam off data

- large background from edge emission and bremsstrahlung

Neutral beam current

110323015 T21 R=83.38cm
Fast Ion Analysis

- The CXRS emission spectrum contains contributions from thermal and fast ions.

Simulated \(H_\alpha\) active emission

Increasing fast ion population with ICRF power

- Fast ions can be detected by a line profile with wings that have higher density than a Gaussian.

- Fast ion signal is small compared to background, so analysis of line profile must be robust against noise.

- One way to quantify a fast ion density is to integrate the raw data over a small wavelength band situated in the wing of the line, corresponding to an energy band of interest. However, this method is strongly sensitive to contamination by bremsstrahlung signal.

- Here, we use a conservative least-squares fitting model.

Wave power
- \(P=3.3\text{kW/cm}^3\)
- \(P=2.5\text{kW/cm}^3\)
- \(P=1.7\text{kW/cm}^3\)
- \(P=0.83\text{kW/cm}^3\)
- \(P=0\text{kW/cm}^3\)
Fitting of $^3$He Fast Ions

- The Student's t distribution (or Pearson VII distribution) is used to fit the distribution
  
  $$p(x) = \frac{1}{\alpha B(m - \frac{1}{2}, \frac{1}{2})} \left[ 1 + \left( \frac{x - \lambda}{\alpha} \right)^2 \right]^{-m},$$

  B is the beta function

- By keeping the number of parameters low, the fitting of noisy data is manageable.

- As $m$ approaches infinity, the distribution approaches a Gaussian. A smaller value for $m$ generates a distribution with higher kurtosis.

  $$\text{excess kurtosis} = \frac{3}{m - 5/2}$$

- Kurtosis measures the amount of density in the wings, thus acts as a proxy for fast ion concentration
The Experiment

Configuration
D majority, $^3$He minority
$I_p = 0.8$ MA, $B_T = 5.6$T
$n_e$ (avg) = $0.6-1.2 \cdot 10^{20}$ m$^{-3}$
LSN equilibrium

ICRF
J antenna at 50MHz, up to 2.5MW
D, E antennas at 80MHz, up to 1MW each

Antenna phasing changed between
90° (co-current wave propagation)
-90° (counter-current wave propagation)
180° (heating phase)

$^3$He concentration was adjusted between shots to switch between mode conversion and minority heating regimes

Selected diagnostic traces from run 1110323

- Shot 4, 200ms $^3$He puff
- Shot 5, 200ms $^3$He puff
- Shot 6, 250ms $^3$He puff
- Shot 7, 300ms $^3$He puff
Absolute Intensity Calibration

- Four techniques used to provide absolute intensity calibration needed for helium density measurement
  - Standard radiometric calibration: during a vessel opening, illuminate the optics with a calibrated source at plasma position
  - Beam into gas: fire beam into pure helium gas and measure emission to acquire relative channel-to-channel calibration
  - Visual bremsstrahlung: Compare our measured bremsstrahlung with bremsstrahlung measurements from $Z_{\text{eff}}$ diagnostic
  - Quasineutrality: Measure CXRS signal in pure helium discharge, infer helium density from Thompson scattering estimate of electron density using quasineutrality. Compare to acquire calibration.

- Beam into gas, visual bremsstrahlung, quasineutrality give comparable results

- Surprisingly, standard radiometric calibration is NOT reliable. Probably due to coating of the optics between experiment and opening. Other techniques an absolute necessity.

- Accurate beam measurement or modeling is also required for the calibration. Beam penetration modeling is done with ALCBEAM simulation code.
Helium density was varied during the course of run 1110323 by adjusting the $^3\text{He}$ puff duration.

Even after $^3\text{He}$ puffing was stopped, some helium remains in the plasma.

$^3\text{He}$ minority concentration is an important governor of heating regime

- Minority heating ($n_{^3\text{He}}/n_e \sim 2\%$), waves mostly absorbed by minority cyclotron resonance. This can generate fast ions.
- Mode conversion heating ($n_{^3\text{He}}/n_e \sim 10\%$), waves mostly converted to short wavelength Ion Cyclotron or Ion Bernstein Waves and directly heat electrons and ions.
Run 1110323, D ($^3$He) plasma

Shots 4-7 are L-mode LSN shots with 0.6 MW 50MHz ICRF from J antenna

$^3$He puff length is varied between shots

<table>
<thead>
<tr>
<th>Shot</th>
<th>$^3$He Puff Duration</th>
<th>$\left\langle \frac{n_{He}}{n_e} \right\rangle^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>200ms</td>
<td>0.05</td>
</tr>
<tr>
<td>5</td>
<td>200ms</td>
<td>0.04</td>
</tr>
<tr>
<td>6</td>
<td>250ms</td>
<td>0.08</td>
</tr>
<tr>
<td>7</td>
<td>300ms</td>
<td>0.12</td>
</tr>
</tbody>
</table>

† Average helium concentration fraction estimated from CXRS
Shot 1110323032, $^4$He ($^3$He) plasma

The plasma is initially ohmically heated, then heated via J port antenna, then J port, D port, and E port antennas.

<table>
<thead>
<tr>
<th>Time</th>
<th>ICRF Power</th>
</tr>
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<tbody>
<tr>
<td>0.50-0.56</td>
<td>0</td>
</tr>
<tr>
<td>0.70-0.76</td>
<td>0.6MW J</td>
</tr>
<tr>
<td>1.30-1.36</td>
<td>5MW D,E,J</td>
</tr>
</tbody>
</table>
Helium Temperature Measurement

- Temperature measurement comes from width of fitted line.
- The convolution of the full Zeeman pattern with a Gaussian was used as the model function for the fit.
- Slit functions (approximated by Gaussian) and dispersion were acquired from measurement of Argon geissler tube spectra.
- The Doppler width is obtained by

\[ \sigma_{\text{Doppler}}^2 = \sigma_{\text{fit}}^2 - \sigma_{\text{slit}}^2 \]
Helium Temperature Profiles

Dashed line: e\textsuperscript{-} temperature from quickfit

Shot 1110323015, t = 1.10-1.16
Shot 1110323017, t = 1.10-1.16

Data is from shot with D(\textsuperscript{3}He) plasma, with ICRF Mode Conversion heating
In run 1110323, after several plasma shots with mode conversion heating, the $^3$He puffing was reduced and then eliminated over the course of several shots in order to test the minority heating regime.

Evidence of fast ions was found using the CXRS system. The fitted line shapes exhibit an increased kurtosis near the IC resonance.

Shot 1110323027, D ($^3$He) plasma

$n_{^3\text{He}}/n_e \sim 0.01$

ICRF: 2.5MW applied at 50MHz (from 0.60s – 1.44s)

1.5MW applied at 80MHz (from 1.00s – 1.50s)

dipole phasing (180°)

![Graph showing spectrum with beam on and beam off, Pearson VII fit and Gaussian fit.]
For shot 1110323027, the He II 4686Å line was fitted with a Student's t model for each channel and the kurtosis is plotted during ICRF 0.70-1.46s before ICRF 0.50-0.56s.

Shot 1110323027
D (³He) plasma, n[³He]/n[e⁻] ~ 0.01
Fast Ion Simulation (AORSA†+CQL3D‡)

Output from CQL3D (version: cql3d_cswim_100829_rza64_nraya1, shot 1100226028, J-port RF: 1.2MW)

a) 2D fast hydrogen distribution at flux surface $R_{\text{mid}}=0.7317\text{m}$

b) normalized spectral patterns for current configuration of channels

Simulated Kurtosis Profile

Computed from CQL3D output
For Hydrogen fast ions, we measure at the Balmer-α line at 6562.8Å.

The Hydrogen measurement has additional difficulties because the fast ion emission overlaps with strong emission from the deuterium fueling species. In order to not saturate the detector, and still maintain sufficient signal to noise in the region of interest, the D-alpha peak must be blocked.

Three methods have been devised:

- opaque or translucent blocking bar in between spectrometer and detector\(^1\)
- moving the D-alpha peak outside the range of the spectrometer
- use of a bandpass or edge filter

We have done proof of principle tests with a bandpass filter which attenuates the D-alpha peak to the same intensity level as the region of interest

Hydrogen Data Analysis

- Real spectra from H-alpha region contains many competing spectral features: beam emission, bremsstrahlung, D-alpha CXRS, D-alpha edge emission, and impurity lines.
- Partial background subtraction is achieved by modulating beam.
- D-alpha lines are strongly suppressed by filter.

Spectrum from shot 1101015025, toroidal channel with notable lines identified. Overplotted with BES, D-alpha CXRS, and fast ion spectra from calculation. Bremsstrahlung and edge D-alpha spectra from fitting.
Fast ion spectrum from a poloidal channel is shown with simulated spectrum overplotted.
Plans

◆ **D<sub>α</sub> blocking bar is being developed**
  – advantages over interference filter as means to block D<sub>α</sub>
    » can get a steeper cutoff
    » can flexibly control cutoff position to get closer to D<sub>α</sub> peak
    » can measure wings on both sides of peak
    » potentially better signal to noise

◆ **New volume phase grating for Helium**
  – 2 or more times dispersion of our current grating
  – better fitting capability, smaller instrument function

◆ **Run additional experiments in helium and hydrogen, with experimental configuration optimized for high fast ion population and low background**
  – low density plasmas with high ICRF power and low impurity concentrations
Unused material